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TITLE: "POLY-PHASE ELECTROMAGNETIC DEVICE HAVING AN IMPROVED CONDUCTOR WINDING ARRANGEMENT"

FIELD OF THE INVENTION

The present invention relates to poly-phase electromagnetic devices such as motors, generators and transformers, of the kind that employ a toothed or slotted magnetically conducive structure into which an electrically conductive winding is wound.

BACKGROUND OF THE INVENTION

The invention has been developed primarily for use in axial flux motors and will be described in detail in reference to this application. However, it will be appreciated by those skilled in the art that the inventive principles are equally applicable to radial flux motors or generators and indeed any other electromagnetic device that includes a slotted magnetically conducive structure into which a conductive winding is wound.

Any discussion of the prior art throughout the specification should in no way be considered as an admission that such prior art is widely known or forms part of common general knowledge in the field.

Background

When trying to optimise the power to size and/or weight ratio of a poly-phase electromagnetic device such as a motor of the kind described above, the packing and spacing of the electrical conductor phase windings within the magnetically conducive base is an important factor. In this regard the use of a magnetically conducive base within which the magnetic flux is constrained has the known advantage of effectively concentrating the magnetic field. This improves functionality of the motor due to a

higher concentration of magnetic flux, at the same time reducing the precision necessary for machining and operating tolerances due to an increase in the minimum separation of air gaps that can exist between stationary and moving parts.

In order to optimise the power density of the device, it is desirable to have a base and winding configuration that is capable of minimising the size and mass of the magnetically conducive base that is required. This in turn will reduce the cost of the device through reduction in construction materials, as well as reducing the parasitic losses within the base material that are present when the device is operating.

This has been a particular problem with, for example, known three phase motors where the phase windings are wound in a wave or lap form progressively one upon the other with each phase offset. This results in uneven slot packing due to physical interference of separate phase windings in the region between slots, known as the end turn, since in some places there must be three windings occupying the same end turn space. This means the slots and base must be sized to accommodate three windings even though those slots will only need to house one winding, resulting in redundant mass and material in the base. Further, the non-active end turns of such an arrangement have to be fairly long because of the increased slot depth and uneven packing in each slot. This results in bulky end turns that make it difficult to adapt such motors for use where housing space is minimal. Further, it is a waste of expensive conductor winding materials and also has significant negative impact on operational efficiency due to unnecessary Ohmic heating in the lengthened conductors.

An alternative method is also employed where extremely long non-active end turns are employed, allowing enough room for each end turn to completely clear the

others and simultaneously filling the slot completely, however the prohibitively long end turn employed in this case causes the same material wastage and efficiency problems as those mentioned with the previous technique.

One solution proposed by the applicant has been to provide a three phase, multiple conductor strand, wave winding arrangement for an axial flux motor that achieves a maximum of two phase end turn overlaps between slots, thus giving reduced end turn lengths around the majority of motor periphery. However, this arrangement still requires external joining of the multiple conductor strands at the ends of each phase winding. This inevitably results in a series of bulging connections that extend radially beyond the rest of the windings concentrated at one location, making efficient packaging of the motor almost impossible. Further the process is very labour intensive and not suited to any convenient form of automation which in turn adversely affects the economic viability of such a design.

It is an object of the present invention to overcome or ameliorate one or more of the discussed disadvantages of the prior art, or provide a useful alternative.

DISCLOSURE OF THE INVENTION

According to a first aspect of the invention there is provided a poly-phase electromagnetic device having n winding phases (where n is greater than 2), said device including:

n separate electrical conductor phase windings, each completed phase winding being in the form of a continuous electrical conductor strand;

a magnetically conducive base having a plurality of slots adapted to receive active portions of the phase windings therein;

each said phase winding comprising a series of interconnected lap form sub-windings, with each sub-winding defining two active arms that extend through two spaced apart non-adjacent slots in the base, the active arms being joined by one or more suitably formed end turn and/or two connecting arms for connection with adjacent sub-windings or terminals;

wherein said phase windings are configured such that on assembly of the phase windings to the magnetically conducive base there is a maximum of n-1 sub-winding end turns overlapping, while the lengths of the end turns are simultaneously minimised.

Preferably the end turns are each offset from the plane in which the active arms are formed to provide clearance between overlapping end turns and so optimise packing density of electrical conductor within the slots of the magnetically conducive base.

In a preferred form the device has three phase windings each made from lap form sub-windings including two or more full loops of conductor strand defining two active arms interconnected by two end turns, each arm and end turn including therein two or more generally co-extending conductor strands, with a lead in and a lead out from said loops defining the respective connecting arms. In one form the device has alternative sub-windings wound in opposite directions, with the completed phase windings intertwined in a plait like configuration to achieve the n-1 end turn packing configuration.

In a first form, the lap form sub-windings are manufactured in the form of discrete bobbins comprising a multiple of conductor strand turns with connection points at each end for joining with an adjacent bobbin of the same phase. In this form,

the connecting arms are configured to extend within gaps formed closely adjacent the magnetically conducive base. In an alternative form the lap form phase windings are formed from a continuous length of conductor strand to form interconnected lap sub-windings which is a structure particularly suited to mass production techniques.

A first preferred method of producing a three phase device according to the invention includes the step of first winding each phase by winding a single conductor strand on to a former to create a string of interconnected lap form subwindings having suitably formed end turns which can then be assembled onto the base either by first plaiting the phases together and then assembling on to the base, or plaiting as they are assembled directly into the base. In another form extended end connectors are used so that the need to plait between overlapping end turns is avoided. This is achieved by forming each phase in two separate half strings as described hereafter.

According to a second embodiment of the invention there is provided a poly-phase electromagnetic device having n winding phases (where n is greater than 2), said device including:

n separate electrical conductor phase windings, each phase winding being made from a single electrical conductor strand;

a magnetically conducive base having a plurality of slots adapted to receive active portions of the phase windings therein;

each said phase winding comprising a series of spaced active arms that extend through spaced apart non-adjacent slots in the base, each active arm being connected with an end turn or terminal in a continuous wave formation;

wherein said phase windings are configured such that on assembly of the phase windings to the magnetically conducive base there is a maximum of n-1 sub-winding end turns overlapping while simultaneously minimising the lengths of the end turns.

Preferably, the phase windings are intertwined in a plait like configuration to achieve the n-1 end turn packing configuration.

In a preferred form, each phase winding is made as a single thickness pressing from sheet conductor material.

In a preferred form, the poly-phase electromagnetic device comprises a three phase axial flux motor or generator.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention will now be described by way of example only, with reference to the accompanying drawings in which :

Figure 1 is a photograph of a prior art three phase multiple conductor strand axial flux stator with n-1 overlap wave winding showing the bulging conductor strand end joins;

Figure 2 is a schematic illustration of a common prior art three phase winding slot packing arrangement;

Figure 3 is a photograph of a first embodiment three phase, axial flux stator which has been wound according to a first aspect of this invention;

Figure 4 is a schematic illustration of an n-1 end-turn overlap winding arrangement for a three phase device according to the invention;

Figure 5 is a computer generated perspective illustration of the wound stator shown in Figure 3, including end terminations for clarity;

Figure 6 is a computer generated perspective illustration of the slotted magnetically conducive base of the stator shown in Figure 5, without the three phase winding;

Figure 7 is a computer generated perspective illustration showing only the three phase winding of Figure 5, without the magnetically conducive base;

Figure 8 is a computer generated perspective illustration of two examples of lap form sub-winding or "bobbin" as would be employed in the example of Figure 5 having opposite winding directions;

Figure 9 is a computer generated perspective illustration of several intertwined bobbins, indicating the relative positions of the bobbins for each phase, as would be employed in the example of Figure 5;

Figure 10 is a computer generated perspective illustration of one of three single complete phase windings as would be employed in the example of Figure 5;

Figure 11 is a computer generated perspective illustration of another embodiment made in accordance with a second aspect of the invention, with only a single conductor strand employed for each phase winding, negating the need for end joins;

Figure 12 is a computer generated perspective illustration of one of three complete phase windings as would be employed in the example of Figure 11;

Figure 13 is a computer generated side illustration showing an alternative location for end-joins in order to allow continuous winding;

Figure 14 is a computer generated perspective illustration showing a half complete winding with an alternative configuration for end-joins in order to allow continuous winding;

Figure 15 is a computer generated perspective illustration showing a prior art press member and press member suitably shaped to form end turn configurations in accordance with this invention;

Figure 16 is a computer generated perspective illustration showing an elongated winding former used for forming lap form sub-windings with offset end turns in accordance with this invention;

Figure 17 is a computer generated perspective illustration showing a linear configuration of lap form sub-windings and magnetically conducive base in accordance with this invention. For explanatory purposes the magnetically conducive base has been extended to show slot location.

PREFERRED EMBODIMENTS OF THE INVENTION

Figure 1 shows a complete prior art three phase axial flux motor/generator stator having a wave winding configuration showing the problems with bulging connections 1, 2, 4 where the multiple strands of each phase winding are joined. The increase in radius of the stator is clearly visible at this point. This is a distinct disadvantage with this form of motor winding, increasing the level of shaft concentric diametric clearance required around the motor and at the same time increasing the cost and size of any casing that might be used. The windings produced are also extremely complex, typically requiring CNC manufacture from copper plate which is expensive and wasteful, or jig winding with a high degree of complexity, as many different bends of different radius are required. As an added level of complexity, once a single strand of winding is complete each turn needs to be end joined, which requires marking each individual end and ensuring that appropriate ends are joined together

and insulated from other ends, all within a confined space. Automation of this process is extremely difficult.

Figure 2 is a schematic diagram which a common prior art method used for stacking a three phase winding within a slotted magnetically conducive base, the diagram being simplified by showing a linear motor/generator stator rather than an axial flux or radial flux stator. The diagram shows three phases 5, 6 & 7, and slotted magnetically conducive base 8. The end turn region shown front on under 7 shows the area where all three phase end turns overlap. Due to all three phases interfering or overlapping in this region, this is defined as a conventional n phase n overlap winding system. As can be seen from the diagram, only a small amount of winding cross section fits into the slot area so slot packing density is poor. An alternative prior art method employs extremely elongated end turns which may be overlapped without such a serious compromise on slot packing density, however this method suffers from an increased material requirement and Ohmic heating losses in the elongated end turns. While these methods for stacking a winding within slots are very simple to construct with each winding being wound separately on top of the previous, they do not lend themselves to an efficient design in terms of either materials use or electrical efficiency.

Figure 4 is a simplified diagram in the same style as Figure 2, however showing an improved winding stacking arrangement in accordance with a part of this invention, whereby end turn interference is reduced. The diagram shows that only two end turns interfere with each other for a three phase system, hence n-1 overlaps in n phases.

Figure 3 shows a complete first embodiment three phase axial flux motor/generator stator in accordance with the first aspect of the invention. The conductive winding shown inserted into the slotted magnetically conducive base can be constructed by several methods. The first method is to construct separate lap elements or "bobbins" comprised of a lap winding each with trailing ends. Half of these elements are wound in a forward winding direction and half in a reversed direction. The reversed lap winding elements are then placed next to each other in the slotted magnetically conducive structure. The forward wound lap winding elements are then stacked in the remaining free slots on top of the reverse wound lap winding elements, in a mirrored fashion. The trailing ends of the bobbins within each phase are then interconnected to form end joins, one end of each of the phases connected together to form a star point and the remaining ends left free as the motor / generator termination point. End joins are required both at the top of the structure 9 and at the bottom of the structure 10. Figure 3 also shows an exemplary arrangement of conductors in individual detail rather than just an envelope containing the windings as the following computer generated images discussed show. It should also be noted from this illustration that the length of each lap in each individual sub-winding changes due to a variation in the length of end turn. This variation tends the complete sub-winding end turn envelope to a shape at each end of the sub-winding similar to part of the surface of a cone, a feature that is a result of the need to travel in a circumferential direction without interfering with the end turns of neighbouring bobbins.

Figure 5 shows a computer generated model of the first aspect of the invention as shown in Figure 3. For clarity, each of the three separate phases is shown in a

different shade. Upper 13 and lower 11 end joins are shown as in Figure 3. For simplicity, the windings have a rectangular cross section which reflects the envelope that would typically contain multiple loops of conductor strand as shown in detail in Figure 3. Winding termination points 12, 14, 15, 16, 17 & 18 show the beginning and end of each respective phase. Typically three of these terminations are connected together in a known fashion to form a star point and the remaining three used as the three motor phase terminations, permutations of which will cause motor direction or phase labelling to change in a known and predictable manner.

Figure 6 shows only the magnetically conducive base portion of Figure 5, with the windings removed. The slots in the structure can be clearly seen in this illustration.

Figure 7 shows only the three phase winding portion with end terminations of Figure 5, not showing the magnetically conducive base. As in Figure 5, each of the three separate phases 19, 20, 21 are shown in a different shades.

Figure 8 shows two types of discrete lap form sub-windings or "bobbins" which suit the embodiment shown in Figures 3 & 5. The two lap elements shown are wound in opposite directions and are not identical, also called an upper and lower bobbin. Whilst end turn bend directions are the same for the two bobbins, the position of the connecting arms is reversed to suit the reversed winding direction. Each bobbin is formed of two or more coextending electrical conductor strands, however as mentioned previously the simplified computer generated diagram only shows the envelope which would enclose those strands. Each sub-winding defines two active arms 26 that extend through two spaced apart non adjacent slots when placed within the base, joined by suitably formed end turns 23, 24 & 25 and two connecting arms for

connection with adjacent sub-windings or terminals 22. Preferably the end turns for a lower bobbin both bend downward and the end turn for an upper bobbin both bend upward as shown. Ideally the connecting arms do not extend directly radially outward, as this would interfere with the end turns. Instead, the arms extend generally axially upward or downward to fit neatly into gaps formed between the end turn and the base to help control the overall packing volume of the device. Figure 9 is a close-up diagram of a portion of Figure 7, showing only four bobbins. This diagram is included to indicate the relative positioning of each bobbin with respect to adjacent bobbins. Two bobbins 28 in this Figure are of the same phase winding and are therefore connected via end connector 27.

Figure 10 shows a single complete phase winding which suits the embodiment shown in Figures 3 & 5. This particular winding is comprised of four upper and four lower bobbins and shows winding terminations. When a completed winding such as the one demonstrated in Figure 10 is to be manufactured by the aforementioned method with discrete bobbins, then eight separate bobbins are required and must be each electrically end joined by a method such as crimping and soldering. Typically, the end joining would be achieved after the bobbins had been inserted into the slotted magnetically conducive base.

Another method and structure refers to lap windings with only a single conductor in each lap, whereby only a single strand of conductor is used rather than two or more coexisting strands. These can be more easily manufactured by a drop forging, pressing or similar methods. Windings formed in this manner can be known as single turn windings, are more simple since they do not require end joining, and may look like the axial flux example shown in Figure 11. Features 29, 30, 31, 32, 33

& 34 represent end terminations of the three phase winding and may be connected in an identical manner as described for Figure 5 previously. This method has advantages in special cases which require high current, torque and/or efficiency, along with simple manufacturing, however is less flexible due to the inability to vary the number of turns in each lap. The windings can either be formed separately for simplicity, since all three windings are the same, or all three formed simultaneously incorporating a star point and termination points at the same time. An example of an individual winding formed using this process is shown by illustration in Figure 12. Note that whilst bobbins are not required for this winding, an "end join region" is still needed to overlap other phases, and this end join region still needs to be bent either up or down to form the required clearances. Similarly to multiple loop aspects, the single loop winding retains end turn features 35 and 36 as well as active arms 37, however connecting arms are not required and are omitted.

Side view illustration Figure 13 shows a completed winding containing three phases 38, 39 & 40, however an alternative location for the connecting arms is shown. This alternative location allows all three phases to be wound in a continuous interconnected fashion. These phases are thus continuously wound without electrical interconnection required, negating the need to end join separately. Phases such as shown may be manufactured by first forming a string of connected bobbins or sub-windings from a single length of conductor, preferably using a CNC wire forming process in the case of thick wire such as depicted in Figure 3 or alternatively a thermally-bonded air coil forming process in the case of more pliable thinner conductor strand. Following this process the completed phases may be plaited together and the completed winding then inserted directly into the magnetically

conducive slotted base. Alternatively, the phases may be plaited as part of the insertion process by taking careful note of insertion order. Beginning with the sub-winding labelled *a* and inserting sub-winding *c* adjacent allows sub-winding *b* to be inserted. By flexing the connecting arms between the first and second sub-winding of phases 38 and 39, phase 38 may then be bent underneath phase 39 and sub-winding *e* inserted. Sub-winding *d* then follows, phase 39 bent around 40 and sub-winding *g* inserted. Similarly *f* can be inserted easily, phase 40 bent around 38 and sub-winding *i* inserted, and so on. It will be appreciated that this process is simple enough to be accomplished by skilled manual labour but can be just as easily adapted to an automated process, and works equally as well for both thick and thin wire.

In some cases it may be necessary to manufacture sub-windings from many turns of thin conductor and a simple and wholly automated process for winding manufacture used. In this situation it may be preferable to increase the length of connecting arms 44, 45 and 46 as shown in Figure 14, which will increase the amount of conductor required for the entire winding but allows an entire set of bottom bobbins to be formed and connected before any top bobbins need to be formed, also negating the need to alternate end turns up and down between interconnected bobbins. This winding may be achieved by using a method similar to that described in European patent application EP0124267 but with a modified press plate. Figure 15 shows the original press plate design 47 disclosed in EP0124267 and modified design showing end turn forming regions 48. An arrangement as shown in Figure 16 using modified press plate 49 & elongated winding former 50 may have a winding 52 formed in a spiral fashion about it, shedding conductors in a lap form 53 into magnetically conducive base 51 directly. Once the desired number of turns have been wound press

plate 49 descends and performs both the function of pressing the sub-winding firmly into slots and forming end turn offsets. Using the longer connecting arm process shown in Figure 14 the entire bottom set of sub-windings can be formed in this manner. Once this is achieved, the process can be repeated on a winding jig of slot configuration and shape identical to the magnetically conducive base, and the resultant second set of bottom sub-windings inverted to form a set of top windings for the original magnetically conducive base once transferred. It may be necessary in this case to have twelve terminations rather than the usual six, however it should be appreciated that the process will reduce construction time and in some situations may give additional advantages.

As some demonstration of the scope of the invention and for clarity, a three phase linear stator incorporating the invention is depicted in Figure 17. Three phases 54, 55 and 56 are shown as well as magnetically conducive base 57. It will be appreciated by those skilled in the art that deforming this linear stator such that the vertical edges at each end of the base are bent to meet then an axial flux stator will be formed, whilst if the horizontal edges at each end of the base are bent to meet then either an inside rotor or outside rotor radial flux stator will be formed depending on whether the upper or lower horizontal edge is used. From this perspective it should be clear that the invention applies just as well to each geometrical configuration.

Accordingly, whilst the invention has been described with reference to specific examples of axial flux motors, it will therefore be appreciated by those skilled in the art that the various aspects of the invention may be embodied in many other forms. In particular the invention suits the common radial flux motor/generator geometry in both internal and external rotor variants. The invention can be equally applied to

other electromagnetic applications such as transformer windings in situations where the improved packing density is desirable. In all cases, the invention applies to n phase systems where n is greater than 2 and a conductive winding is wound into a magnetically conducive base.